Wall Force produced during a Disruption

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It's important for ITER to determine the forces produced on the surrounding conducting structures during a plasma disruption.

The disruption is simulated using the M3D code. The code solves resistive MHD equations with parallel and perpendicular thermal transport. The plasma resistivity is calculated self consistently from the temperature as $T^{-3/2}$. The plasma is bounded by a thin, resistive wall of thickness δ. The magnetic field perturbations outside the wall are calculated with Green's functions (GRIN code). The jump in the magnetic field across the thin wall gives the wall force.

Wall Force

The current in the wall is given by

$$\mathbf{J}_w = \nabla \times \mathbf{B} \approx \frac{\hat{\mathbf{n}}}{\delta} \times [[\mathbf{B}]]$$

where $\hat{\mathbf{n}}$ is the outward normal to the wall, and

$$[[\mathbf{B}]] = \mathbf{B}_v - \mathbf{B}_p,$$

where $\mathbf{B}_v$ is the vacuum magnetic field just outside the wall, and $\mathbf{B}_p$ is the magnetic field in the plasma, just inside the wall.

The normal component of the force is

$$F_{wn} = \hat{\mathbf{n}} \cdot \mathbf{J}_w \times \mathbf{B}_w = -\frac{1}{\delta}[[\mathbf{B}]] \cdot \mathbf{B}_w$$

where the continuity of the normal component of the magnetic field, $\hat{\mathbf{n}} \cdot [[\mathbf{B}]] = 0$ was used, which follows from $\nabla \cdot \mathbf{B} =$. Inside the wall assume that

$$\mathbf{B}_w = \frac{1}{2}(\mathbf{B}_v + \mathbf{B}_p).$$

The normal wall force can be expressed

$$F_{wn} = \frac{1}{2\delta}(|\mathbf{B}_p|^2 - |\mathbf{B}_v|^2).$$

It has a simple physical meaning. It is the difference in magnetic pressure across the wall, divided by the wall thickness.

The tangential, ℓ component of the wall force is

$$F_{w\ell} = \frac{1}{\delta}(\hat{\mathbf{n}} \cdot \mathbf{B})||\hat{\ell} \cdot \mathbf{B}||.$$

where $\hat{\ell} = -\hat{\mathbf{n}} \times \hat{\phi}$. The physical interpretation is

$$F_{w\ell} = \mathbf{J}_\phi \hat{\mathbf{n}} \cdot \mathbf{B}$$

Disruption Simulation

In the following M3D is used to calculate a disruption. The initial state is an ASDEX equilibrium, AUG 12/09/2004 #014271, calculated by CHEASE, and written to a file in EQDSK format. This was read into M3D and used to generate a mesh and initialize a nonlinear simulation. The initial equilibrium had $q = 1.1$ on axis. Multiplying the magnetic flux ψ, and the toroidal current by a scale factor, the pressure by the square of the scale factor, an approximate near equilibrium initial state was obtained with $q = 0.52$ on axis. This state models what might have occurred if outer layers of plasma were scraped off during a VDE. The resulting state is highly unstable to an external kink. A small $m = n = 1$ perturbation was added to the plasma and it was allowed to evolve nonlinearly.

In the simulation the Lundquist number was chosen to be $S = 10^5$ on axis and $S = 10^2$ at the wall. The resistivity is calculated self consistently as $T^{-3/2}$, where T is the temperature. When the temperature decays during the simulation, the value of S drops, although its value is held fixed at the wall. The wall constant, the wall resistivity η_w divided by wall thickness, was chosen $\eta_w/\delta = 2.5 \times 10^2$.

The initial magnetic flux is shown in Fig.1(a). In Fig.1(b), at time $t = 47\tau_A$, the flux contours resemble a typical VDE, with flux penetrating the upper boundary. In Fig.1(c), at $t = 66\tau_A$, the flux surfaces have broken up as the plasma disrupts.

The temperature contours during this evolution are shown in Fig.2. The initial state is in Fig.2(a). At the the intermediate time $t = 47\tau_A$, in Fig.2(b), the temperature contours are already deviating from the flux contours, indicating a large three dimensional effect. By time $t = 66\tau_A$, in Fig.2(c), the temperature contours lack evidence of confinement.

The time history of the run is shown in Fig.3.

The wall force and current is shown in Fig.4. A time history of the peak wall force F_{wn} is shown in Fig.4(a). It grows to about 0.12 at $t = 60\tau_A$, followed by a brief spike to 0.24 at $t = 65\tau_A$. The spatial distribution of F_{wn} at $t = 66\tau_A$ as a function of ϕ (vertical axis) and poloidal coordinate ℓ, is shown in Fig.4(b). The poloidal coordinate

$$\ell = \int_0 d\ell,$$

where $d\ell$ is the incremental distance along the wall boundary, starting from $Z = 0$ at the outer boundary and proceeding counterclockwise. It appears that the largest force is at the top of the boundary. Fig.4(c) is a vector plot of the wall current at the same time and in the same coordinates. It can be seen that there are large currents at several locations.

In future simulations, higher resolution will be used to try to extend the simulations further time. Other initial states corresponding to different disruption scenarios will be tried.

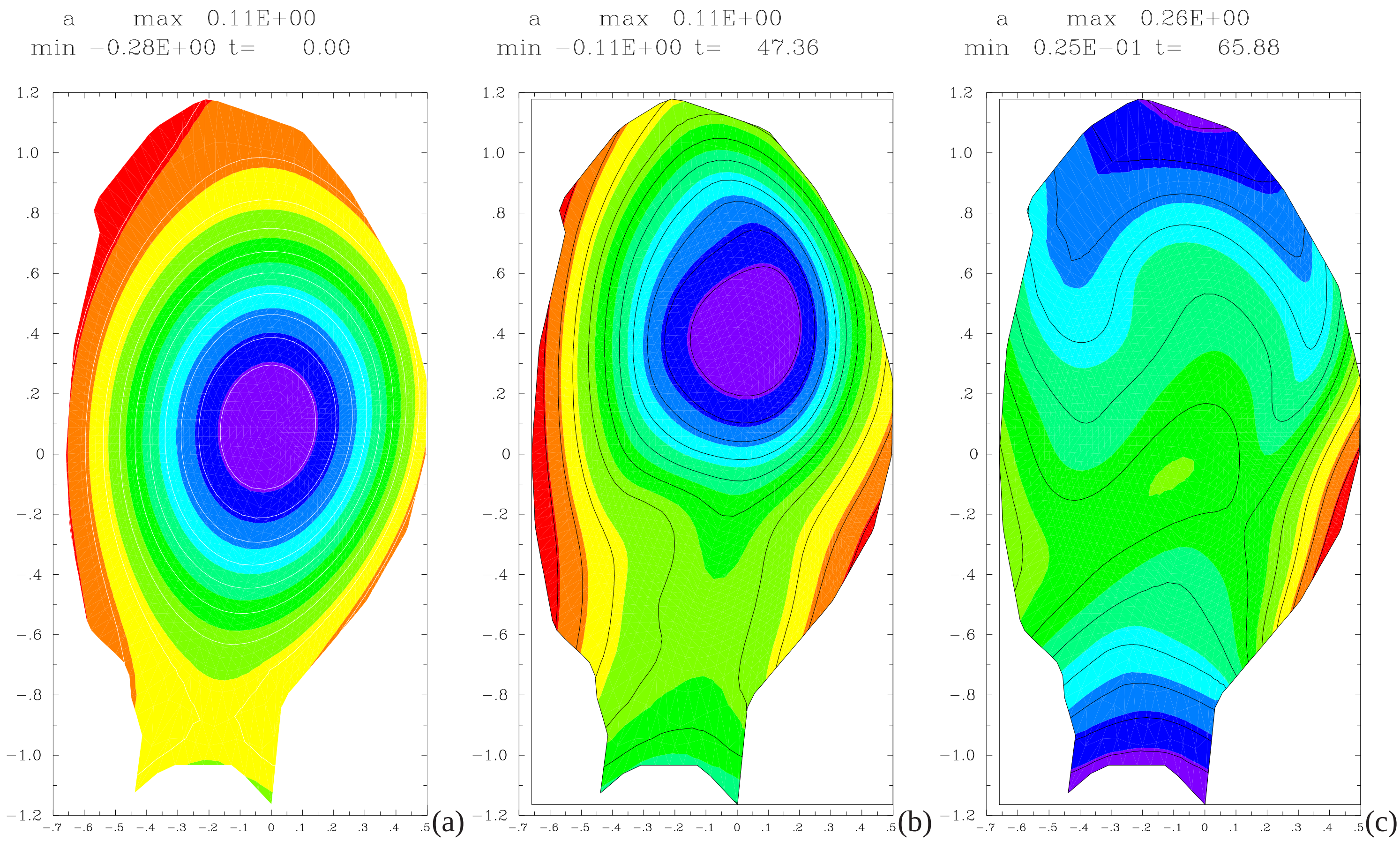

Figure 1: (a) initial magnetic flux contours of rescaled ASDEX equilibrium reconstruction. (b) magnetic flux contours in the poloidal plane with toroidal angle $\phi = 0$, at time $t = 47\tau_A$. The flux resembles a typical VDE. (c) magnetic flux contours in the poloidal plane with toroidal angle $\phi = 0$, at time $t = 66\tau_A$. The plasma has disrupted and there are no closed poloidal flux contours.

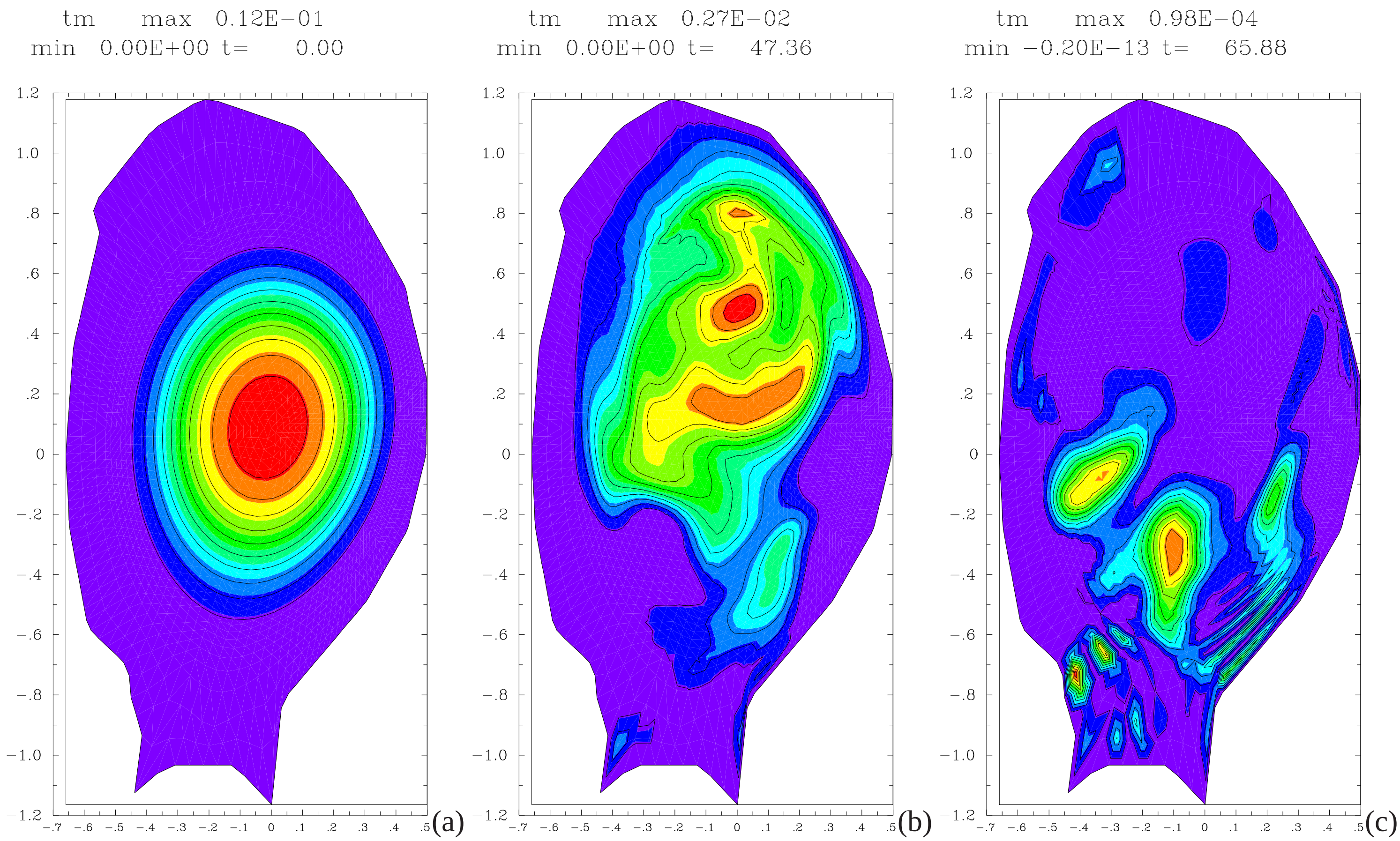

Figure 2: (a) initial temperature contours in the poloidal plane with toroidal angle $\phi = 0$. (b) temperature contours at $t = 47\tau_A$. (c) temperature contours at time $t = 66\tau_A$, in the poloidal plane with toroidal angle $\phi = 0$.

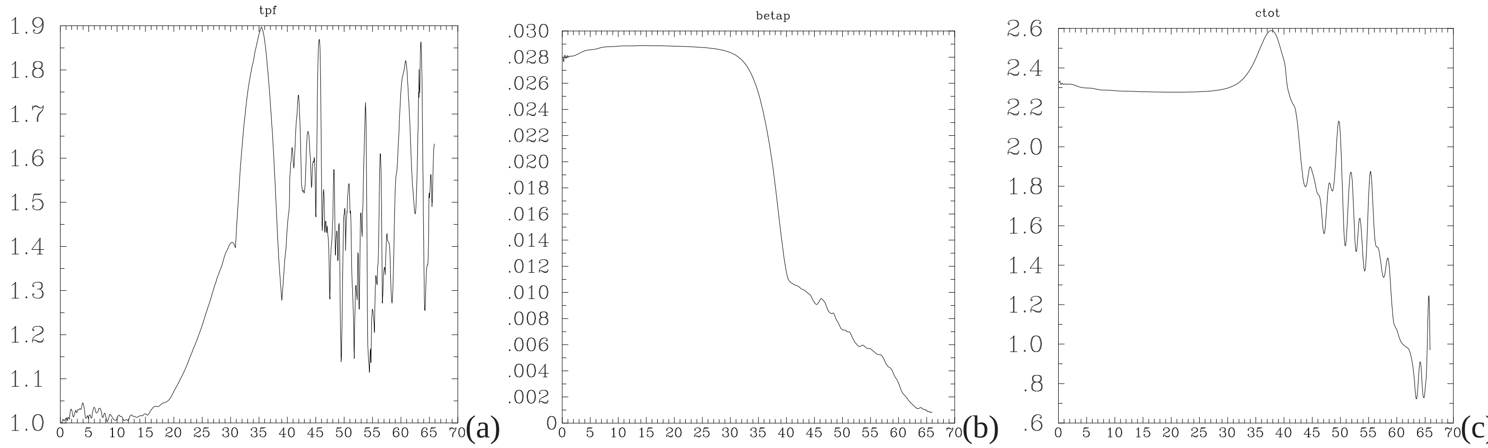

Figure 3: (a) time history of the toroidal peaking factor. The TPF reaches a maximum at about time $t = 35\tau_A$. (b) time history of the total plasma pressure. The temperature collapse begins at about $t = 35\tau_A$, when the TPF is maximum. The initial drop is rapid, followed by a slower decay. (c) time history of the total toroidal current. The current collapse begins soon after the temperature collapse, but is more gradual and unsteady.

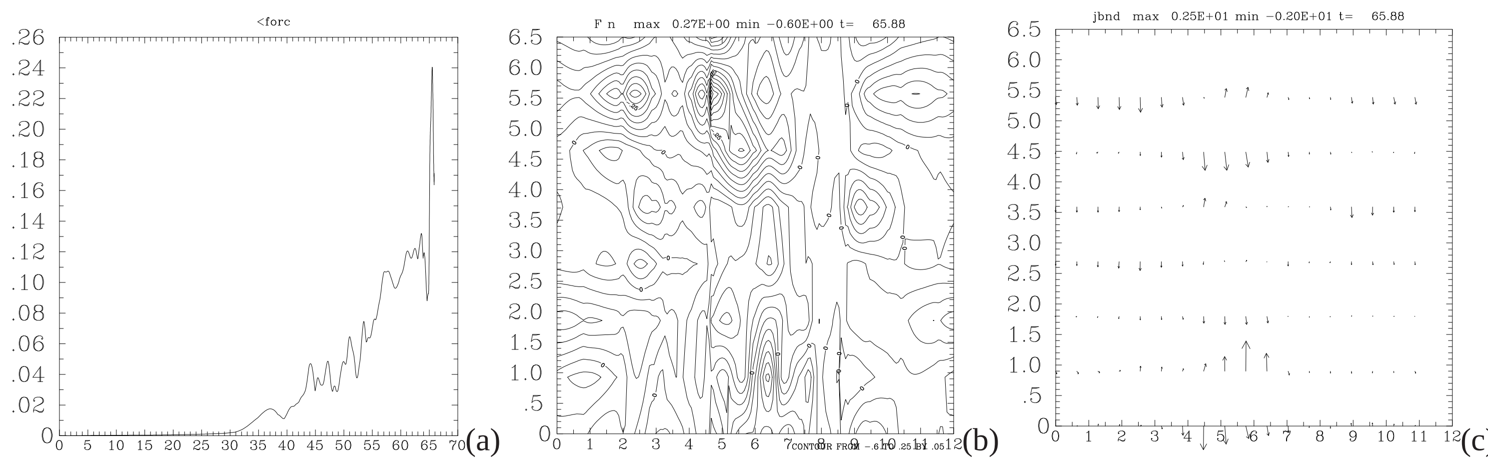

Figure 4: (a) time history of peak normal force on the wall. The force saturatures at about $F_{wn} = 0.12$ at time $t = 60\tau_A$, followed by a brief spike to twice that value. (b) normal wall force F_{wn} at time $t = 66\tau_A$, as a function of ϕ (vertical axis) and poloidal coordinate ℓ. (c) wall current at time $t = 66\tau_A$, as a function of ϕ (vertical axis) and poloidal coordinate ℓ.